

Strung Together

*THE Cultural Currency OF
String Theory AS A
Scientific Imaginary*

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CHAPTER I

Introduction

String Theory as a Theory of Everything

String theory is reputed to have begun in 1968, when a postdoctoral fellow named Gabrielle Veneziano, working at CERN,¹ one of the world's leading high energy physics laboratories, proposed a solution to a vexing problem concerning the interaction of subatomic particles in the nuclei of atoms. He accomplished this by using a formula he had found in an eighteenth-century mathematics text.² Two years later, three other theorists—Yoichiro Nambu, Leonard Susskind, and Holger Nielsen—independently suggested that Veneziano's redeployment of this antique mathematical function implied that the particles that formed the nuclei of atoms were not actually zero-dimensional point-particles, but rather, extended out into an extra dimension.³ While Nambu and Nielsen described this hypothetical object as a “harmonic oscillator”—a term common to both classical mechanics and quantum theory, Susskind was the first to liken it to a vibrating string (“Dual” 483). As many popular accounts go, in what one might describe as a leap of imagination, a radical reconceptualization of the ordinary string was adapted to theoretical high energy physics in order to replace the point-particle of quantum theory and serve as the fundamental constituent of the universe.

In essence, string theory declares that the cosmos is made up of strings: they are either open or closed, possess tension, and vibrate. The degree of tension corresponds to the frequency of vibration which, in turn, determines what form a string takes. These strings are miniscule—on the scale of 10^{-33} centimeters.⁴ When experimental physicists attempt to observe them with their instruments, the colliders and detectors at CERN and other such laboratories—that currently can probe distances of about 10^{-17} centimeters—they appear, so the theory contends, as the myriad point-

particles so accurately delineated by quantum theory. As of yet, strings have not been observed in nature.

Since 1968, string theory has blossomed into a fully fledged attempt to reconcile the two established theories of matter and force in the universe—quantum theory and general relativity—into one mathematically consistent and empirically valid formalism. Public awareness of string theory grew tremendously with the publication of the first book-length popularizations in the late 1980s. Thereafter, string theory popularizations have been published—and enthusiastically consumed—with increasing regularity. One can explain this in part due to several factors: the radical transformation of “common sense” that string theory as a theory of physical reality suggests; the controversial nature of string theory’s status as science; and perhaps most significantly, the tradition within contemporary Anglo-American culture for theoretical physicists to serve as the custodians and purveyors of a particularly resonant form of fundamental truth; namely, that which constitutes the cosmic order.⁵ Having captured the popular imagination, one now observes string theory imagery cropping up with increasing frequency in both popular culture and literature.

This book represents the first investigation into string theory as a specifically cultural phenomenon. String theory, in particular, provides a fruitful topic for this sort of approach for two important reasons. Firstly, it is a relatively new theory, having only been studied for about forty years. String theory has begun to seep into public awareness only in the past twenty-five years or so, beginning with the publication of Michio Kaku’s *Beyond Einstein* in 1987, followed by F. David Peat’s *Superstrings and the Search for the Theory of Everything* and *Superstrings: A Theory of Everything?*, edited by Paul Davies and Julian Brown, both published in 1988. String theory’s public profile grew immensely in 1994, with the success of Michio Kaku’s follow-up, *Hyperspace*. As the subject of cultural study, string theory represents, to borrow a favorite trope of the popularizers themselves, relatively unexplored territory.

Secondly, string theory would seem, by its nature, to lend itself to literary adaptation: as a theory of everything, it is currently the leading scientific attempt to unify into one consistent theoretical framework the known matter in the universe with the known forces. As such, it would potentially form the foundation for all other scientific knowledge.⁶ In this sense, theoretical physics—which deals, in all its mathematical and imaginative esotericism, with the world on the largest and smallest of scales—has always been fertile ground for a cultural imagination hoping to bind the cosmos to human-scale, quotidian concerns. Given string theory’s even further re-

move, it would seem to be all the more vulnerable to such imaginative appropriation.

This book's core approach is to examine the cultural currency of string theory by means of a concept I call a *scientific imaginary*.⁷ Drawing primarily on the work of French philosophers of science Michèle Le Doeuff, Gaston Bachelard, Michel Serres, and the American cognitive linguist George Lakoff, the following chapter defines this pivotal term *scientific imaginary*, in part by contrasting it to a scientific realism that sorts "pure" concept from "playful" or "illustrative" image. In a scientific enterprise such as string theory, an imaginary is a complex of images that, while ostensibly set off from concept, nevertheless problematizes it. These images serve as doubles for mathematical arguments, yet they also possess their own inferential relations distinct from this structure of correspondences. In this sense, a congeries of images that in one valence are bound individually in one-to-one correspondence to mathematical expressions, in another valence, together constitute an autonomous whole, an imaginary. Such an imaginary is marked as scientific inasmuch as it retains its reference to what a culture recognizes as scientific practice—in the case of string theory, with a particular, dynamically defined amalgam of methods and reasons, empiricisms and logics, with an emphasis on the plural. The following chapter offers several examples of scientific imaginaries in an epistemological and cosmological context in order to demonstrate how the concept can be employed to analyse textual presentations of string theory. This chapter shows that, in effect, the work of a scientific imaginary is fourfold: one, it grounds scientific concept in familiar human-scale experience; two, it mediates between human agency and the agency of the objects a theory manifests; three, it invests those objects with substance; and importantly, four, it situates scientific theory within a larger imaginative context. Without this connecting tissue, so to speak, scientific knowledge such as string theory would have no epistemological footing.

In addition to its timeliness, part of this book's value lies in the fact that it brings to bear on string theory, and importantly, its technical discourse, a novel method of close reading that synthesizes developments in contemporary cognitive linguistics with more familiar literary critical techniques. Furthermore, it offers new insights into the complications that arise in the consumption by a non-specialist audience of string theory popularizations—insights that pose important implications for the consumption of science popularizations in general. Ultimately, this book suggests a novel way for scholars, critics, and lay readers to contextualize and evaluate the adaptation of scientific ideas by popular culture and literary texts.

This book makes four key claims. First, that the imagination is central to the production of string theory as scientific knowledge. Second, we must read string theory popularizations carefully, since the imaginary that they present often engenders a particular ideological bias. Third, there are clumsy and nuanced ways for imaginative writing to adapt string theory ideas, and by implication, ideas from theoretical physics in general. And fourth, that string theory as an imaginary reflects, paradoxically, both an archaic sensibility and a contemporary culture where the ethos of globalization dominates.

As mentioned earlier, since technical articles serve as the main vehicle for the production of string theory as scientific knowledge, a principal concern of this investigation will be, in chapter 3, a careful consideration of them. I have chosen these articles because they represent key episodes during string theory's historical development. Significantly, I will focus on the expository prose that surrounds and frames the core mathematical content of these key technical articles. Such a reading strategy readily concedes that the ostensibly conceptual content of the technical articles; namely, the mathematics, speaks to an exclusive and highly specialized audience. The authority to judge the legitimacy of the science as it is practiced through mathematical argument within string theory technical articles rests with the professionals themselves. Nevertheless, the chapter examines several crucial instances where images—specifically the string, brane, and extra dimension—enter the technical discourse within a specific article, and thus contribute to and, in many respects, serve to determine, an imaginary. Chapter 3 also investigates the extent to which such an imaginary can be said to cohere from article to article—through the technical discourse as it develops historically. Since images refer to specific mathematical expressions, a key question will be: to what extent can the complex of these images, an imaginary, be said to cohere? Furthermore, how do the terms and the images associated with these terms come to gain a common cultural currency? How do they become conventionalized as a specifically epistemological imaginary, as a means of knowing the world?

With popularizations—the subject of chapter 4—the dynamics of expression change. In my survey of string theory popularizations, I have found them to fall into three basic categories: one, accounts written by string theorists that take a positive, relatively uncritical stance; two, accounts written by physicists who do not specialize in string theory but who treat it as a secondary topic, with varying degrees of critical distance; and three, accounts that are openly critical of string theory.⁸ Chapter 4 examines the first type of popularizations for the following reason: they are

heavily invested in string theory's scientific legitimacy—and in its ultimate institutionalization—and therefore are highly interested in communicating string theory as a coherent, meaningful theory. Yet, since they omit the mathematics out of explicit consideration for an audience they assume is mathematics-averse, an imaginary takes precedence over pure conceptual content.⁹ In these popularizations, the exposition of string theory comes to be, in many respects, a vehicle for the substantiation of what Michel Serres calls an “endo-epistemology” (*Conversations* 128). A way of knowing the world becomes a self-contained, all-encompassing means of structuring the relationship between an imagined human agency and a radically remote and alien cosmos.

Strictly speaking, from a realist perspective, a discourse such as that constituted by string theory popularizations would be suspect if it made claims about the objective world without direct recourse to an agreed-upon empiricism and a self-consistent logical structure—the purview of specialists. The rest of us—a lay readership, including the scientists who specialize in other fields—are simply not in a position to confirm the legitimacy of string theory's empirical or mathematical consistency. In effect, the non-specialist reader must take the truth-value of the content of a popularization on a certain form of faith endemic to contemporary Anglo-American culture; that is, faith in the authority of “hard” science to present the heretofore “hidden” reality of our world. Accordingly, to accept string theory as a legitimate science is, to a certain extent, an act of belief. Chapter 4 investigates the extent to which the imaginaries in three string theory popularizations, which are representative of the first type, are, as Caroline Jones and Peter Galison put it, “a revealed truth otherwise hidden,” dependent wholly on the authority of the narrator, or conversely, something “self-contained because it ‘speaks for itself’” (354).

The 1999 publication of Brian Greene's *The Elegant Universe* represents another watershed moment in popular awareness of string theory. When organizing a collection of creative writing inspired by string theory, entitled *Riffing on Strings* (2008), I noticed that many authors credit Greene specifically with introducing them to it.¹⁰ In *Science on Stage*, Kirsten Shepherd-Barr draws attention to the recent surge in output and reception of science plays. A noteworthy subgrouping of the trend of the past decade in science plays are those that are specifically string theory-themed. Chapter 5 represents the first sustained attempt at critical attention to imaginative texts, including some of these plays, which engage with string theory. For the purposes of this investigation, I will define imaginative texts as texts where the imagination is understood to be primary, as with drama, fiction, and

poetry. The following are issues relevant here: the salient differences and similarities between the imaginary such texts present in relation to popularizations and technical discourse, and the extent to which these texts, in effect, reproduce both a string theory imaginary and an endo-epistemology that supports and sustains that imaginary.

Together, this constellation of texts—the manifold technical articles, popularizations, and imaginative treatments—come to constitute a string theory imaginary. While this imaginary is uniquely heterogeneous—a miscellany of images, internal relations amongst those images, and correspondences between the images and an objective world, supposedly manifest through mathematics, beyond its own structure—within this imaginary, a pattern of flows emerges. Images move unidirectionally from technical exposition to popularizations to the literary. The concluding chapter explores the implications of understanding a form of scientific knowledge such as string theory as an imaginary in a wider sociological context. The discussion relates string theory as a late twentieth and early twenty-first-century social phenomenon to broader cultural trends; for example, globalization. In tracking the migration of string theory images from one discourse to another, I will pay particular attention to the role an imaginary plays in the transmission, substantiation, and adaptation of a science such as string theory to contemporary Anglo-American culture, considered broadly. We will then be in a position to ask: to what extent does a string theory imaginary constitute another supporting “pillar” in the edifice of scientism, where scientism is understood as an unreflective faith in the monologic omnipotence of science? Or does this string theory imaginary—with all its ambiguities and ambivalences—serve to frustrate scientism?

By ordering the chapters as I have (an introduction to string theory, a chapter on the concept of a scientific imaginary, string theory technical discourse, popularizations, then imaginative writing), I do not mean to imply the prescriptive reinforcement of an established hierarchy of scientific knowledge. Rather, as a scholarly monograph, this book is descriptive inasmuch as it respects the mandate to provide credible evidence in accounting for the intertextual flow of string theory ideas and images from one discourse to another. Accordingly, it attempts to account for the actual flow of string theory images and ideas as it has occurred over the course of the past four decades, which has been, as previously stated, predominantly unidirectional.

As chapter 5 shows, much contemporary imaginative writing that engages with string theory tends to reproduce this conventional hierarchy, in large part, by deferring reflexively to string theorists’ cultural authority as guardians of cosmic truths. Yet I do not see imaginative writing as

doomed categorically to being only a weak reflection of string theory technical discourse. Through a close reading, in particular, of Carole Buggé's play *Strings* and Brenda Hillman's poem "String Theory Sutra," chapter 5 explores how imaginative writing can and, in these noteworthy cases, does challenge the epistemological assumptions of scientific realism, while nevertheless avoiding the lazy distortions of some representations of string theory. Lastly, the concluding chapter provides an account of how string theory itself may be shaped imaginatively by the historical and cultural technoscientific milieu out of which it has emerged.

One intriguing possibility would be to rearrange the contents of the book so that its structure embodies its claim about the primacy of imaginaries in string theory as a scientific culture. Such an approach would reflect a sensibility that emphasizes the importance of play in its methodological framework as an implicit epistemology, in keeping with one of the book's important influences, Michel Serres. This would be an altogether different book, one more akin to a philosophical essay in the style of Serres. Yet I suspect that a hypothetical Serres-esque essay that endeavored to foreground non-scientific cultural influences on string theory as the technical discourse of a professional community (for example, how science fiction may have shaped the work of the prominent string theorist Ed Witten) would have a difficult time justifying its evidence and, as a consequence, would risk making the kinds of catachreses that the likes of Alan Sokal find so farcical. As such, the ordering of the book reflects, in some respects, a methodical pragmatism more in keeping with the style of another of its key theoretical sources, George Lakoff.

String Theory's Emergence

For those readers who may be unfamiliar with string theory, what follows in this introductory chapter is an account of the key features of string theory within the context of its historical development—in effect, how string theory attempts to reconcile and thus move beyond its predecessors—general relativity and quantum theory. To avoid complication, this description of string theory hews closely to the standard narrative found in most string theory popularizations. While both general relativity and quantum theory have achieved canonical status within the high energy physics community, string theory remains very much a work in progress. As such, this chapter also touches upon the ongoing debate in the broader theoretical physics community concerning string theory's legitimacy as science.

Thomas Kuhn writes of science progressing not holomorphically, as a smooth and continuous process of accretion, but rather in a series of fits and starts, of one “paradigm” of “normal science” being ousted by another in a paroxysm of revolutions or “shifts” (6, 10). String theory might exemplify just such a paradigmatic shift—upending one “conceptual box,” as Kuhn puts it, one set of theoretical commitments, in favor of another (5). Broadly speaking, string theory concerns itself with the interactions that occur between the fundamental objects of nature, described in terms of fundamental forces. Established physical theory currently posits four fundamental forces: electromagnetism; the strong nuclear force, which acts to bind the particles that comprise the nuclei of atoms together; the weak nuclear force, which contributes to radioactive decay; and gravity.

As we shall see in chapter 4, string theorists themselves often narrate the history of the theory as a romance where the heroic physicist struggles to reconcile all the known particles with all the known forces—a noble quest for that ultimate prize, a “theory of everything.” It is important to acknowledge, though, that when string theorists speak of a theory of everything, they mean something specific to the problems that the profession considers legitimate: their notion of “everything” does not imply, at least directly, every domain of scientific knowledge (e.g., applied physics, astronomy, chemistry, biology, and so on), but rather the problem of conceiving a quantum theory of gravity. A quantum theory of gravity would integrate the formalism and the body of experimental evidence that constitutes quantum theory, the currently accepted theoretical explanation for, loosely speaking, the realm of the very small—subatomic matter, which is subject to electromagnetism, the weak and the strong nuclear forces—with the theory of general relativity, which currently is employed most fruitfully in treating gravity in the context of interactions of large objects: apples, planets, stars, galaxies, the entire universe. This is a specific concern with specific problems relating to attempts at synthesizing the mathematical formalisms of quantum theory and general relativity. The attempt to integrate the “conceptual box” of quantum theory with the “box” of general relativity must yield a precise formalism. This formalism would represent a third, entirely distinct “conceptual box,” with its own cache of legitimate problems, its own set of concisions and symmetries. This third paradigm, though, must be backward-compatible, to borrow an expression from software engineering: it must not contradict any of the demonstrated accuracies of its predecessors with respect to observed phenomena. Yet historically, this requirement of backward-compatibility becomes ever more stringent as solid evidence in diverse experimental domains mounts. As

such, the problem of fitting a new paradigm to the growing and seemingly incompatible bodies of evidence requires ever more sophisticated formalisms. String theorists today wrestle with the logical structure of their core conceptual commitments, its fundamental objects and how to reconcile these objects with the requirements of quantum theory, to retrofitting the framework of quantum theory onto the string, so to speak, while simultaneously coaxing the string into the formal constraints of the tensor algebra and Riemannian geometry of general relativity.¹¹

With that in mind, let us backtrack briefly in order to describe the historical and conceptual context out of which string theory has emerged. Since string theory concerns itself with unifying the known fundamental forces of nature, an appropriate starting point would be the mid-1800s. While Sir Isaac Newton had formalized a theory of universal gravitation in 1687, it was James Clerk Maxwell, building on the work of Michael Faraday, who proposed in 1865 a theory to account for what were then recognized to be two other forces of nature distinct from gravity—electricity and magnetism. Experiments demonstrated that electricity and magnetism behave in ways that the Newtonian theory could not explain adequately, limited as it was to describing the world in terms of rigid bodies and the “invisible” force of gravity that instantaneously attracted them. Furthermore, Faraday observed that electricity and magnetism both behaved in a remarkably similar fashion. Maxwell was able to model the behavior of electricity and magnetism through a set of equations (known, appropriately, as *Maxwell's equations*) that mathematically expressed the concept, not of an instantaneous force interanimating rigid bodies, but of a pervasive, disembodied *field*.¹² Maxwell's was a theory of electromagnetism, in which this force permeates absolutely flat and infinite Newtonian space as a harmonically oscillating field with associated values for frequency, momentum, and charge—positive, negative, or neutral. Maxwell went on to make the prediction that there are electromagnetic waves that travel at the speed of light and that also possess light's properties of polarization. Heinrich Hertz confirmed his prediction experimentally in 1888; light has since been considered a particular manifestation of electromagnetic energy—with distinctly field-like behavior.

In 1905, building on the work of Maxwell, Hendrik Lorentz, Henri Poincaré, and Hermann Minkowski, among others, Albert Einstein addressed an important problem that Maxwell's hypothesis concerning light had opened up in Newtonian mechanics. In the Newtonian universe, momentum is infinitely cumulative: in theory, if a person travelling near the speed of light flicks on a flashlight, the light that emerges from the bulb

should travel at the speed of light plus the speed at which the person is moving. But since light was and is known to possess a finite, constant speed, any scenario with a speed beyond the speed of light is physically impossible. Einstein proposed that the accumulation of speed in the physical universe does not behave as Newtonian theory predicts: it behaves asymptotically—speed always approaches a maximal limit, the constant speed of light in a vacuum, measured at approximately 186,000 miles per second. Or, as Kaku concisely puts it, “The speed of light is the same in all constantly moving frames” (*Hyperspace* 82). Among other things, Einstein’s solution—his theory of special relativity—expresses this limit on the possibilities of speed. Einstein realized that this has startling implications for our understanding of time. In *The Elegant Universe*, Greene offers a vivid illustration of one of these counterintuitive implications using two astronauts in space, named George and Gracie, who are equipped with space suits and special jet packs.

[I]magine that the relative speed of George and Gracie when they pass and are moving apart is 99.5 percent of light speed. Further, let’s say that George waits 3 years, according to his clock, before firing up his jet-pack for a momentary blast that sends him closing in on Gracie at the same speed that they were previously moving apart, 99.5 percent of light speed. When he reaches Gracie, 6 years will have elapsed on his clock since it will take him 3 years to catch her. However, the mathematics of special relativity shows that 60 years will have elapsed on her clock . . . In a real sense, George’s motion has made him a time traveler, albeit in a very precise sense: He has traveled into Gracie’s future. (44–45, emphasis in original)

According to special relativity, Greene summarizes, since “observers in relative motion will have different perceptions of distance and time . . . time slows down when an object moves relative to us because this diverts some of its motion through time into motion through space” (25, 50). Both time and space are, in effect, integrally pliant phenomena: space-time. We do not notice this relationship in our daily experience, because the motion we perceive never approaches the speed of light.

In 1907, Minkowski formulated special relativity in terms of a four-dimensional geometric, which has since come to be known as *Minkowski space-time*. What distinguishes Minkowski space-time from its predecessor—the Euclidean space used by Newton—is the affording of time a space-like status. In Newtonian mechanics, time remains isolated as a phenomenon. In Minkowski space-time, time forms an integral part of the total “fabric”

of space. In this sense, Minkowski space-time is not simply a physical space, but an epistemological abstraction: a manifold that captures the counterintuitive interrelationship between space and time. Special relativity presents the image of the universe as a dynamic, interrelated whole, often imagined as a fabric.¹³ According to the theory, the essence of this cosmos, as a system, is a particular kind of change; namely, the force of movement as rotation not just through space, but time as well. Since no moving body can travel faster than the speed of light (for if it were to reach the speed of light, time would stop), light itself forms an absolute boundary in Minkowski space-time. This is often called in the theory a “light cone,” which defines the limits of causation, since an object may never contact or communicate with another object outside this cone.

In 1915, Einstein expanded the space-time of special relativity to incorporate acceleration.¹⁴ With his theory of general relativity, he posited a fundamental equivalence between acceleration and the force of gravity within a space-time framework. A famous equation, the Einstein Field Equation, expresses this relationship using tensor algebra. A tensor describes a collection of quantitative attributes that are associated with particular coordinates in the geometric space of the system. The Einstein Field Equation equates energy and momentum (the stress-energy tensor) with space-time curvature (known generally as the Einstein tensor). Unlike special relativity—with its flat Minkowski space-time—the geometry of general relativity is Riemannian: the tensor of information having to do with stress-energy, with the density and flux of energy within the system, manifests as the curvature of space-time itself, not just the motion of objects through it. Space-time bends and warps in dynamic response to the motions and densities of energy and matter that constitute it. General relativity has helped make numerous predictions that have been borne out in subsequent experiments; for example, that the universe is expanding; that it originated with a Big Bang; and that, given enough matter concentrated in one region in space, gravity there can become so powerful that not even light can escape, forming a black hole.

In the 1920s and 1930s, while Einstein’s theories of special and general relativity were forcing a radical revision of Newtonian cosmology, an international cadre of physicists, led by Einstein, Max Planck, Ernest Rutherford, Niels Bohr, Erwin Schrödinger, Werner Heisenberg, Paul Dirac, Max Born, and Louis de Broglie, among others, was focusing its attention on theorizing the realm of the very small. Out of their collaborations emerged quantum theory, which offered up its own paradigm shifts to problematize Newtonian theory. If we include the contributions of the physicists

that succeeded that initial generation, including Richard Feynman, David Bohm, Murray Gell-Mann, Sheldon Glashow, Steven Weinberg, Abdus Salam, and many others, we can summarize that quantum theory¹⁵ has made the following contributions.

(1) The concept of the *quantum*, or the discretization of energy. In quantum theory's historical development, this eventuated in the disarticulation of the atom into a seemingly ever-expanding array of subatomic particles—with exotic names like muon, tau, neutrino, and charm quark—organized within the standard model into groups based on symmetries, or shared attributes.¹⁶ The fundamental image of the quantum particle is a point in space with no internal extent. In addition to having a variable position and momentum, particles may possess other distinguishing attributes—constants such as rest mass, spin (angular momentum), charge (positive, negative, or neutral), color (red, green, or blue), and flavor (up, down, strange, bottom, top, or charm).¹⁷

(2) Along with electromagnetism, the discovery and incorporation of two other forces: the weak nuclear force, which contributes to a certain form of radiation decay, and the strong nuclear force, which binds the nuclei of atoms together. It is important to note that current versions of quantum theory do not account for the force of gravity. So, in a significant sense, it is not comprehensive.

(3) Wave/particle duality, which asserts that subatomic quanta behave both like waves and like particles. The wave behavior of the quanta is expressed in the theory in terms of *wavefunctions*, which describe the probability distributions that define a particle and that provide predictions for the given attributes, such as position and momentum, about to be observed.¹⁸

(4) Quantum theory further formalizes this characteristic wave/particle ambiguity through the Heisenberg uncertainty principle, which attests that, because of a given particle's dual nature as both wavefunction and point-particle, there exists an inversely proportionate possibility of measuring with precision either the particle's position or its momentum. The Heisenberg uncertainty principle, generally applied, can also pertain to the relationship between a given particle's energy and time, as well as other specific pairs of attributes. In effect, it demonstrates the fundamental inability to know with absolute precision a pair of attributes of a given particle, if those attributes have a mutually dependent relationship within the mathematical formalism of the theory.

(5) Consistent with the ambiguity implied by wave/particle duality, quantum theory can describe forces in terms of particles as well; these force particles are sometimes called “messenger” particles, treating the force act-

ing between two “matter” particles as if it were a “packet” of information. For example, the theory can describe the strong nuclear force that binds quarks within the nucleus of an atom as the exchange of a “messenger” particle called a *gluon*.

(6) Quantum theory’s earliest incarnation, quantum mechanics, assumes a background of absolute space and a distinct and absolute time dimension; it does not incorporate the constraints of special or general relativity. Contemporary quantum field theories do incorporate special relativity, thus a relativistic, albeit flat, four-dimensional Minkowski space-time. But, as mentioned earlier, no widely acknowledged quantum theory accounts for gravity—neither the force itself, hypothesized as a messenger particle called a *graviton*, nor the effects of the curvature of space-time in general relativity.

In addition to being an exceedingly effective explanation for the dynamics of the subatomic world, quantum theory has contributed or given outright birth to many important technologies including applied chemistry, nuclear fission, the laser, the diode, the electron microscope, and the transistor, integral to all electronics—including the computer. Yet in spite of quantum theory’s demonstrated predictive accuracy, many theorists would agree that quantum theory feels somewhat like a kluge,¹⁹ with its unwieldy proliferation of subatomic particles organized into symmetry groups,²⁰ the seventeen or so numerical constants that must be inserted into the formalism and that the theory has no way of explaining through its own internal logic,²¹ the qualification that only quantum theories that are “renormalizable” yield workable results,²² and lastly, the unsettling epistemological ambiguity, previously mentioned, between wave and point-particle states. Such theoretical deficiencies leave most theorists (and a fair share of experimentalists as well) unconvinced that, with quantum theory to explain the subatomic realm and general relativity to describe the universe as a whole, we currently have in our possession a true theory of everything.

The universally accepted standard model of quantum theory came to maturity in the 1970s. Since then, much theoretical inquiry has concerned itself with the margins of the two canonical theories; in effect, with scenarios that arise when general relativity and quantum theory come into direct conflict. These scenarios occur when physical phenomena are simultaneously very large (e.g., high energy densities) and very small. Two such scenarios that often occupy contemporary high energy physicists are black holes, where massive amounts of matter get compressed into a quantum-scale space, and the split second immediately following the Big Bang, where the entire universe was compacted into a comparably micro-

scopic extent. In these physical extremes, both theories break down and, as such, provide a strong incentive for theorists to concoct a new theory—one that reconciles quantum theory with general relativity and thus would allow them to explore with greater predictive power these exotic physical scenarios—black holes and the very early universe.

String Theory's Development

The string theory proposed by Nambu, Susskind, and Nielsen in the early 1970s attempts to explain the mysterious dynamics of the strong nuclear force. Their theory is called *hadronic string theory*. The protons and neutrons that make up the nuclei of atoms are classified as *hadrons*, those subatomic particles that experience the strong nuclear force. Yet in the early 1970s, the most promising theory for explaining the strong nuclear force was quantum chromodynamics, a point-particle field theory. Quantum chromodynamics posits the existence of a new category of particles called *quarks*.²³ Quarks possess a novel form of charge, arbitrarily designated “color”—hence the “chromo-” in chromodynamics. Through a battery of new experiments that took advantage of more powerful accelerators, the high energy physics community came to the consensus that quantum chromodynamics was overwhelmingly more successful at explaining the strong nuclear force than hadronic string theory.

Nevertheless, a small group of theorists persisted in their expansion of string theory. In 1974, John Schwarz of the California Institute of Technology and Joël Scherk of the Ecole Normale Supérieure proposed that string theory was not merely a theory of the strong nuclear force, nor even of the more comprehensive grouping of subatomic particles that comprise the standard model. In their reformulation, known as *bosonic string theory*,²⁴ they argued that one of the string's vibrational patterns possesses properties that correspond to the then posited messenger particle for gravity, the graviton. Since bosonic string theory incorporates the force of gravity through the graviton, Schwarz and Scherk felt they could claim that theirs was a legitimate quantum theory of gravity; it predicted gravity.

Subsequent investigation showed, however, that their revision and expansion of string theory suffered from its own slew of inconsistencies. For example, in order to be consistent with quantum theory, bosonic string theory requires not the four space-time dimensions of relativity, but twenty-six space-time dimensions.²⁵ Needless to say, for most physicists committed to the principles of scientific realism—however philosophically nuanced—

this was a difficult pill to swallow. Scientific realism holds as a fundamental tenet that there is an objective world independent of our capacity to know it. Should overwhelming evidence gathered using a diversity of methods confirm the existence of a phenomenon in the world, it ought to be taken to be objectively real; for example, that the universe consists of three spatial dimensions: length, height, and breadth. In addition, bosonic string theory predicts the existence of a new kind of particle, called a *tachyon*, that possesses the reality-defying feature of negative mass—or, from a complementary perspective, propagation beyond the speed of light.²⁶

Meanwhile, experiments with particle accelerators in the mid-1970s were probing the internal structure of hadrons and finding them decidedly point-like at the scale of about 10^{-16} centimeters. This was glaringly inconsistent with the proposed size of the string in bosonic string theory, which, at 10^{-16} centimeters, should reveal its extended dimensionality. Throughout the rest of the decade, experimenters confirmed, time and again, the predictive accuracy of the standard model of quantum theory. Accordingly, quantum theory became further institutionalized, while string theory languished in relative obscurity on the peripheries of accepted practice.

In string theory lore, this all changed in 1984 when Michael Green at Cambridge University, who had been working with John Schwarz at Caltech for several years on improving the theory, published what Brian Greene has dubbed a “landmark” paper.²⁷ The paper claimed to resolve the problems that had marginalized string theory for the past ten years. Many string theorists refer to the appearance on the scene of this revised theory by Green and Schwarz as “the first superstring revolution”—the moment when string theory became a legitimate contender for the highly anticipated “theory of everything.” Green and Schwarz accomplished this by incorporating supersymmetry into the theory (hence the “super” in “superstring”). Supersymmetry is a principle that provides for the pairing of fundamental particles, organized in the standard model into the two moieties of bosons and fermions,²⁸ in a mathematically coherent way such that many of the inconsistencies in quantum field theory—or string theory—may cancel out. The standard model accounts for its spectrum of subatomic particles by sorting them into the three distinct symmetry groups that are juxtaposed. Supersymmetry merges these three groups into one “supergroup.” Supersymmetry also suggests the possibility of the unification of all four fundamental forces into what is sometimes called *supergravity*.²⁹

As a consequence of the manner in which it organizes the particles into one “supergroup,” supersymmetry predicts the existence of a new array of partners for the known quantum particles—what are sometimes referred

to as *sparticles*.³⁰ The incorporation of supersymmetry into Green and Schwarz's superstring theory requires the model to reduce the number of posited space-time dimensions from twenty-six down to ten. It also does not generate particles of negative mass, the so-called tachyons. Another hallmark of their new superstring theory is that it recalibrates the string tension from the relatively large (and untenable) scale of the original bosonic string theory down to about the Planck scale, or 10^{-33} centimeters. Green and Schwarz's particular version of superstring theory, which has since come to be known as Type I superstring theory, also predicts the graviton, thus reinvigorating string theory's claim to be a theory of quantum gravity.

Shortly after Green and Schwarz's theory reignited a burst of interest within the high energy physics community, other theorists proposed alternative and potentially competing versions of superstring theory—whose composition depends largely on how supersymmetry is incorporated into the theory's overall structure. These competing versions of superstring theory are known, respectively, as Type IIA, Type IIB, Heterotic $SO(32)$, and Heterotic $E_8 \times E_8$.³¹ Further work in the late 1980s and early 1990s showed that, although they share certain features, the various theories diverge enough to suggest a significantly contrasting picture of physical reality. Brian Greene describes the mood within the string theory community since then: "This has been an embarrassment for string theorists because although it's impressive to have a serious proposal for the final unified theory, having five proposals takes significant wind from the sails of each" (*Elegant* 284). For physicists, one criterion by which they judge a theory is that it has a certain inevitability; that the theory reproduces precisely the specificity of observed phenomena—in the case of string theory, that it generates the exact particle spectrum of the standard model, or a justifiably extended version thereof. That five plausible versions of string theory have come to coexist suggests that these theories, although they share a strong conceptual continuity, may also have built into their internal logic too many degrees of freedom, too many possible permutations and thus physical consequences—a feature that directly contradicts the principle of inevitability. The embarrassment for string theorists lies in these versions' excessive flexibility. They lack the requisite rigidity for generating (or retroactively predicting) the observed particularities of the physical world. Speaking of general relativity, Lawrence Krauss writes: "The complexity of the theory means that we still have not yet fully understood all its consequences; therefore we cannot rule out various exotic possibilities" (*Physics* 34). This observation could apply to string theory as well. The multiplicity

of—as yet, not disproved—versions, coupled with an overall lack of understanding as to their physical implications, contributes to a climate within string theory where “exotic possibilities” cannot be ruled out.

Work on the five competing versions of string theory continued more or less independently until 1995, when, at the premier annual string theory conference (called *Strings* and held that year at the University of Southern California), Edward Witten, from the Institute for Advanced Study, presented a paper³² that launched what the community has come to regard as the “second string theory revolution.” Witten’s solution to string theory’s embarrassment of riches is to suggest that its five versions are actually different perspectives, symptoms of the perturbative methods employed in the theories’ mathematical formalism, that all point toward one unified framework, which he dubs “M-theory.”³³ He proposes that the ten space-time dimensions called for in the earlier theories are also an approximation; M-theory requires eleven.³⁴ With this and other adjustments, Witten claims that the five theories (and one more called eleven-dimensional supergravity) can be organized into one meta-theory, due to relations that depend on certain mathematical constants and the geometry of space-time itself. As one of its entailments, Witten’s revisioning of string theory posits a central role for drumskin-like objects that extend into two or more spatial dimensions—what are called *membranes*, or simply, *branes*.³⁵ Branes behave similarly to strings. Some more recent versions of string theory even define the string as a *one-brane* and a point-particle as a *zero-brane*.

It is important to note here, though, that Witten himself, along with the rest of the string theory community, is acutely aware of M-theory’s limitations. M-theory gestures toward a quantum theory of gravity, but does not actually codify it. Much of the work in the field since 1995 has focused on the search for a more coherent and precise formulation of M-theory. M-theory has also spawned its own revisions. For example, in 1996, Cumrun Vafa, of Harvard University, published a paper that proposed an “F-theory,” which calls for twelve rather than eleven space-time dimensions, along with other modifications in the geometric structure of its space-time.³⁶ As we shall see later, when one considers the arguments of string theory’s detractors, the efforts of the past fifteen years, though resulting in a veritable deluge of papers, have yet to provide a third “revolution”—one that can claim to offer a formalism that possesses the required inevitability for a universally convincing model of physical reality.³⁷

While some string theorists work on refining M-theory, another sub-discipline attempts to reconcile the currently conceived formalism of the theory with known astrophysical phenomena. A paper authored by Juan

Maldacena of the Institute for Advanced Study epitomizes such efforts.³⁸ Maldacena argues that if the geometry of a certain ten-dimensional string theory model is reconfigured, it becomes consistent with the holographic principle, which stems from studies of information loss in black holes and posits that a physical model of $(n - 1)$ dimensions can correspond exactly to a physical model of n dimensions; an effect analogous to a holographic projection. For the purposes of the discussion at hand, what is significant here is that string theorists are actively borrowing concepts from astrophysics in order to make their models more robust, so that they better corroborate more experimentally grounded physics. Another example of this is a paper³⁹ published by Vafa and Andrew Strominger, also of Harvard University, that undertakes a similar calculation of the information states of a certain type of black hole using a string theory formalism.

These types of approaches seek to mold string theory such that it better conforms to astrophysics. Other approaches attempt to inject string theory into astrophysical models. Shortly after Witten's revolutionary M-theory proposal of 1995, Joseph Polchinski, of the University of California, Santa Barbara, posited the existence of another structure where open strings are fixed onto a time-like membrane, which he called a "D-brane."⁴⁰ An alternative cosmological model based on Polchinski's concept of the D-brane has complicated conventional Big Bang theory. In a D-brane-based scenario, the four space-time dimensions of our universe may exist as a "braneworld" within a larger and enveloping eleven-dimension metaverse, often called *the bulk*. One version of braneworld cosmology has replaced the Big Bang with a "Big Splat"; two braneworlds cyclically collide to provoke the expansion of our braneworld universe.⁴¹ Other speculations occupy themselves with concepts such as tears in the "fabric" of space-time, wormholes, infinitely extended extra dimensions rather than miniscule, curled-up ones, or gravity "leakage."⁴²

Yet another subdiscipline of string theory that has emerged post-M-theory aims to integrate the theory more fully with general relativity, beyond predicting the existence of the graviton (the force of gravity) as the consequence of one particular string-vibrational mode. Like special relativity, M-theory's precursors assume an essentially flat space-time background.⁴³ As discussed earlier, general relativity shows that space-time exhibits curvature. The very topology of space-time warps and ripples in direct relation to its own gravitational pull; that is, in proportion to its energy density. Yet a quantum theory of gravity implies a fully quantized universe, where space-time itself is no longer infinitely divisible and infi-

nately extensive, but rather, granular and finite. The underlying gravitational field, composed of a multitude of gravitons linked together in a kind of matrix or fabric, constitutes space and time. Were we able to probe this fabric at a sufficiently tiny scale, we would encounter lacunae in space itself—a thoroughly counterintuitive notion.⁴⁴ Work concentrating on such a granular space-time fabric has led string theorists to attempt to constitute space-time itself with a certain form of zero-brane,⁴⁵ whose behavior at the Planck scale, the theorists contend, is best described not by the commutations and anticommutations of Riemannian geometry, but by a formalism developed in the early 1990s by the French mathematician Alain Connes called *noncommutative* geometry.⁴⁶ Edward Witten has also attempted to integrate M-theory with another background-independent space-time theory based on general relativity—Roger Penrose’s “twistor” theory.⁴⁷

String Theory’s Status as Science

While string theory has grown, in some sense, to dominate the discipline of theoretical physics, it has also managed to attract an increasing number of critics. Almost unanimously, they point out that string theory seems to concern itself only tangentially with observational data, and as such is more an imaginative speculation than an empirically based science. String theorists would not disagree that this lack of testability is a direct consequence of the scale of the fundamental string—the Planck scale. Current accelerator technologies are only capable of probing scales about a thousand times smaller than the atomic nucleus. The Planck scale is smaller than that by a factor of more than a million billion—analogueous to inspecting with a telescope individual atoms in the Andromeda galaxy, which is approximately 2.5 million light years from Earth (Krauss, *Hiding* 209). Even the Large Hadron Collider at CERN is unable to probe such remote scales.⁴⁸ Some experimentalists calculate that in order for an accelerator/collider to have the capacity to probe the Planck scale, it would require more energy than all the energy in the entire known universe combined.⁴⁹ Others contend that the energy required merely outstrips several times over the total power output available on Earth, assuming current technologies and resources. Theorists such as Brian Greene hope that the Large Hadron Collider will serve the purpose of further legitimizing string theory, either by confirming the existence of sparticles, the particle duals predicted by supersymmetry, or by providing solid evidence for the existence of extra dimensions.

Nevertheless, although string theory attempts to incorporate supersymmetry, it is not the only theory to do so. Many high energy theorists would consider the existence of sparticles merely circumstantial evidence.

String theorists also suggest that astrophysics might provide evidence for the existence of strings. Some astrophysicists currently study the cosmic background microwave radiation that persists as a kind of residue or record of the explosive expansion of the universe immediately following the Big Bang. Certain interpretations of string theory suggest that this explosive early universe may have left traces of superstrings stretched out to macroscopic proportions—cosmic strings. New instruments such as LIGO (Laser Interferometer Gravitational-Wave Observatory) and LISA (Laser Interferometer Space Antenna), designed to detect gravitational waves, may help to confirm the existence of such cosmic strings.⁵⁰ One group of physicists has proposed an experiment to probe, albeit indirectly, extra dimensions larger than the Planck scale, yet still microscopic—a scenario that certain versions of string theory predict.⁵¹

Several prominent physicists have become outspoken critics of string theory, including Roger Penrose, Sheldon Glashow, Lawrence Krauss, Philip Anderson, Lee Smolin, and Peter Woit.⁵² Many detractors evoke the Popperian argument that string theory, since it is so far removed from experimental observation, has the inexcusable quality of being unfalsifiable.⁵³ They also point to string theory's embarrassment of riches—the nearly endless proliferation of allowed physical scenarios due to the theory's excessive flexibility, its myriad degrees of freedom. To claim legitimacy on the grounds that certain string theory versions can generate “semi-realistic” particle spectrums strikes these critics as entirely unconvincing.

Some theorists evoke the “anthropic principle” in their defense of string theory's seemingly excessive degrees of freedom.⁵⁴ One prominent braneworld scenario suggests that the “bulk” multiverse may contain upwards of 10^{500} four-dimensional braneworlds, such as our universe, each with their fundamental physical laws tuned slightly differently—this multiverse being termed “the Landscape.” Given such a multiverse, proponents argue that we find ourselves in a universe with the precise configuration of physical laws that can support the formation of galaxies, stars, planets, life, and ultimately, sentient life, simply because we are here to observe just that. Since we exist, such a universe, tuned precisely to accommodate our existence, must be possible. The anthropic principle is what Susskind would call an “environmental” argument; it suggests no inevitability based on first principles as to the particular physical properties of our observable universe. These properties are merely a product of circumstance.⁵⁵ Many physicists, including some string theorists, find such anthropic arguments

to be entirely unsatisfactory. They expect a theory to express a more stringent degree of inevitability, to explain fundamental causal relationships in a self-consistent manner.⁵⁶

String theory also poses many unresolved and seemingly intractable mathematical impasses. What follows is a brief summary of these issues. No one has been able to formulate a string theory using a non-perturbative method,⁵⁷ which most view as essential to making the theory coherent on extremely small scales. Furthermore, M-theory itself has yet to be successfully quantized—a necessary prerequisite for full validity. The theorists specializing in string *field* theory, a version of string theory that attempts to integrate background independence,⁵⁸ similarly, have made little tangible progress. Furthermore, string theory has yet to establish the fundamental inevitability of the string itself. Strings, whether open or closed, along with branes of various dimensions and configurations, emerge from various theories depending on how they are formulated. No version of string theory demonstrates a self-evidently particular composition of such fundamental objects. Furthermore, a fundamental principle such as the equivalence principle⁵⁹ in Einstein's general relativity has yet to be formulated within the context of string theory. Ed Witten has suggested that string theory might confirm the notion that space-time itself is an emergent phenomenon, not a fundamental assumption.⁶⁰ Rather than “plugging” a space-time background into the formalism as an initial condition, string theory ought to be able to produce space-time through its own machinations, and thus, be able to “predict” the existence of space-time. Krauss points out that string theory might make a genuine prediction with respect to one epistemological puzzle still very much unresolved—that of calculating the energy of empty space itself, or what is often called in the literature *dark energy*.⁶¹ But string theory has yet to do so.

Finally, there is the problem mentioned previously as to the physical status of string theory's proposed extra dimensions. Barton Zwiebach writes:

In superstring theory a similar calculation fixes the dimensionality of spacetime to the value of $D = 10$. The fact that string theory cannot be a good . . . quantum theory in any arbitrary dimension shows that string theory is very constrained. Even more, since the dimension of spacetime is uniquely selected by the requirement of consistency, we can say that string theory predicts the dimension of spacetime! (231)

While bosonic string theory requires twenty-six space-time dimensions, superstring theory calls for ten—the $D = 10$ of the calculation to which

he refers. What Zwiebach finds so remarkable is that by forcing superstring theory to conform to the requirements of quantum theory and special relativity, in order to be mathematically self-consistent, its space-time background must have ten dimensions. In effect, the mathematics of superstring theory emphatically predicts that the cosmos must possess these extra dimensions.

Critics such as Penrose and Krauss argue that these extra dimensions may be nothing more than “mathematical artifacts.” Krauss asks:

What is the utility of an extra hidden dimension if ultimately nothing is hidden except the existence of the extra dimension? And what is the practical meaning of extra dimensions if you can experience all there is to experience without actually moving into them?⁶²

Krauss seems to suggest that string theorists, by arguing for the physical existence of extra dimensions, have fallen into that epistemological trap, described by Gaston Bachelard, where “what is real but hidden has more content than what is given and obvious” (*New* 31–32). In effect, form takes precedence over substance in the string theorists’ implicit epistemology. The theoretical formalisms have more reality than what we can interact with physically, directly. It is sufficient to “grasp” theoretically the string in order to grant it the status of being real.

Yet our bodies move in three dimensions: up and down, left and right, back and forth. As such, an emphatically shared and intuitively self-evident experience compels us to acknowledge that we live in a physical universe of three spatial dimensions. String theory conceptualizes time in a comparable manner to special relativity. Within the formalism, time is defined as a space-like dimension—an axis, much like the forward and back our bodies locomote along, composed of an array of points. These points are measured out into a metric relative to the motion of an arbitrarily chosen body (for the metric of seconds, etc., the motion of the earth around the sun). Within the theory, the idea of a spatial dimension, a fixed line of sight that allows one to locate objects in space (and time) becomes readily multiplied beyond the limits of commonsense physical space. Counterintuitively, we must extrapolate extra dimensions from the familiar back and forth, up and down, and left and right motion of bodies through space. In a sense, it is impossible to imagine a fifth, a tenth, or twenty-sixth dimension in their own “literal” terms. Our imaginations, grounded as they are in our bodily experience, are simply not equipped to process such an alien abstract space.

The mathematics of extra dimensions itself is not such a novelty. Math-

emathical operators, such as the Hamiltonians employed by quantum theory, frequently make use of them to map extra-spatial physical attributes such as spin and charge to spatial dimensions. Special relativity formulates the physical world in extra dimensions—four total, three of space, and one of a space-like time. As noted previously, this counterintuitive binding of space with time constitutes, in and of itself, an abstract space. Yet theoretical physicists in general would be loath to concede that the extra dimensions of special relativity also represent what Krauss calls “mathematical artifacts.” In order to offer any legitimate promise of expanding our capacity to intervene in the causal structure of the physical world, the formalism of string theory must necessarily account for a massive amount of empirical data, gathered from a vast body of preceding theory and experiment. Most of this observational data is only indirectly accessible to our apprehension, by way of mediating instruments. Even these instruments, accelerators and colliders such as the Large Hadron Collider, yield abstract data that must be reconciled to the formal framework. Yet it would seem that a string theorist’s insistence on the existence of these extra dimensions results from an allegiance to a particular epistemology that I have called *realist*. The three chapters that follow explore certain significant features of this realist epistemological commitment on the part of string theorists and the consequences that such a commitment has on the status of the theory’s fundamental objects as objective phenomena—strings, branes, and extra dimensions.

To echo Krauss, even if some battery of future experiments—such as the search for sparticles or macroscopic extra dimensions—were to confirm string theory’s prediction that the universe has ten (or eleven, twelve, or twenty-six) space-time dimensions, that would not necessarily invalidate a debate concerning the epistemological status of these extra dimensions and what implications they would pose for our understanding of string theory’s claim to objective reality. Positive results from such experiments would only confirm string theory’s efficacy—that it provides accurate prompts for intervening in the causal structure of the world, prompts for an intervention still ultimately grounded in embodied experience. And we live with the practical certitude that our bodies exist in three dimensions: they move up, down, left, right, back and forth. To perhaps state the obvious, a dimension is an abstraction that formalizes this motion in such a way that we may project the event of bodily motion into remote perceptual terrain. The potency of this abstraction, originating from the concept of a line of sight or the ordered rows and columns of an agricultural field, lies in its capacity to accommodate the additional information needed to de-

scribe accurately the full range of attributes of the phenomena within these remote perceptual domains.

Physical theories would seem to function admirably in the following fashion: a theory reconceptualizes physical reality in a precise way; physicists then draw inferences and design experiments based on that reconceptualization—what Kuhn calls the work of “normal science.” The experiments, satisfactorily diverse in methodology and independently repeated, then either validate or falsify the theory. What we could only imagine and never experience directly then attains the status of stable scientific knowledge. Accordingly, string theorists claim that the precise formalism of the theory predicts the existence of extra dimensions. The history of theoretical physics in general has demonstrated repeatedly the efficacy of this approach. The broad acceptance of a revolutionary theory is predicated inevitably on its making a bold prediction that contradicts the prevailing intuition—the accuracy of which is subsequently confirmed through some newly fashioned experiments.

The initial institutionalization of general relativity is a prime example. Sir Arthur Eddington’s 1919 expedition to the African island of Príncipe to observe a solar eclipse confirmed Einstein’s prediction concerning the shifting of light due to the gravitational influence of massive bodies such as the sun. Thereafter, theorists and experimentalists labored to design further experiments that took as their template the warped and pliant space-time formalized by general relativity. String theorists practice a specific form of epistemology—with its own covenant of behavioral and symbolic conventions, validation procedures, and legitimate problems—that privileges a categorically objective reality, or to use a conventional image, a “deeper truth.” While consensus is relatively easy to build with respect to the self-consistency—or correctness—of a given piece of mathematics, as critics complain, string theorists currently struggle to produce more than just flashy mathematics, however self-consistent. They have yet to provide experimentalists with more emphatic direction on how to corroborate the theory with evidence. Yet in spite of its lack of a champion such as Sir Arthur Eddington, who legitimized the then seemingly implausible theory of general relativity, string theory enjoys a great deal of popular recognition, if not implicit support. In lieu of evidence, string theorists themselves, along with a public that ultimately funds their livelihoods through institutions such as universities, would seem happy to see their investigations continue on the basis of two things: one, a body of interesting mathematical problems to solve; and two, as the following chapters detail, a compelling imaginary to describe the cosmos.

Those keen to philosophize quantum theory have focused principally on its most counterintuitive idea—the dual nature of its fundamental wave/particle as elucidated, in part, by the Heisenberg uncertainty principle. Meanwhile, once enough experimental evidence had accumulated, the correctness of quantum theory’s formalism, for instance, the Schrödinger wave equation, was never much in doubt. To this day, the high energy physics community may use quantum theory without being able readily and coherently to imagine it.

In its current state, string theory’s continuing institutional prestige is complicated by the dubious empirical status of the science itself. Those critics anxious to fix string theory’s meaning to a political agenda have dismissed it as “pomo” junk science—the product of a self-involved cabal of mathematics-intoxicated speculators. More moderate detractors argue that it lacks a sufficient degree of inevitability to justify all the resources and manpower devoted to it. They point out that, at best, string theory is “semi-realistic” in its backward-compatibility—its capacity to replicate the canonical standard model. Although string theory excites many with its promise of incorporating, along with supersymmetry, the force of gravity into quantum theory, one critical inference that follows from the string’s formal structure; namely, the incredibly minute scale of strings themselves, makes any potential experimental validation difficult to anticipate.

String theorists argue that the existing body of experimental evidence and the formal constraints of the mathematics they employ serve to discipline their speculative impulses, to bring them back down to earth. They insist that string theory’s formal component dictates that it must progress by a consensus beholden to the strictest of rules. Yet, as the following chapters explore in more detail, the formalism’s imaginative complement may very well serve as a repository for an *informal* content for which the mathematical arguments themselves cannot account. String theory’s formal complexity, its exclusionary technical opaqueness, its facility for speculative model building, and its tenuous status as science all conspire to leave it ripe for a reading that calls attention to the pivotal role the imagination plays in its technical exposition and, following on from that, in its wider cultural currency.

As we have seen, to evoke string theory as a unitary whole obscures its bewildering heterogeneity. One might speak of a plurality of string theories, save for the fact that certain more recent versions no longer even posit the string as their fundamental object. When cataloguing string theory, one is obliged to include M-theories, F-theories, brane theories, and Landscape theories, among others. As U.S. Supreme Court Justice Potter

Stewart famously wrote of pornography in *Jacobellis v. Ohio*, in lieu of a precise definition—“I know it when I see it.”⁶³ The use of the single term *string theory*, which stands for a complex of concepts and ideas, would seem to be merely a matter of linguistic convention and practical convenience. Nevertheless, in light of this problem of multiplicity, the close readings that follow of string theory-themed texts will explore the extent to which continuity in the presentation of string theory as an imaginary does indeed suggest a uniform string theory imaginary as a cosmic order.

Notes

Chapter 1

1. CERN is the *Organisation Européenne pour la Recherche Nucléaire* (European Organization for Nuclear Research). It is located on the border between France and Switzerland, just west of Geneva. It is home to the Large Hadron Collider.

2. This formula is called the *Euler beta function*, after the eighteenth-century Swiss mathematician Leonhard Euler. See Veneziano, “Construction of a Crossing-Symmetric, Regge-Behaved Amplitude for Linearly Rising Trajectories.” Henceforth, endnotes will cite the full name of technical articles in order to provide context. For all other texts, endnotes will only cite details sufficient for readers to refer to the bibliography.

3. See respectively: Nambu, “Quark Model and the Factorization of the Veneziano Amplitude”; Susskind, “Dual Symmetric Theory of Hadrons I”; and Nielsen, “An Almost Physical Interpretation of the Integrand of the N-Point Veneziano Model.”

4. This scale is known as the Planck scale, after the German physicist Max Planck. Of the Planck scale, John Schwarz writes: “one way that it is sometimes expressed is to say that the Planck scale is to the size of an atom as an atom is to the size of the solar system” (*Superstrings* 71).

5. John Brockman’s promotion of a “third culture” provides a contemporary example of the supposed “moral” authority of scientists in general: “The third culture consists of those scientists and other thinkers in the empirical world who, through their work and expository writing, are taking the place of the traditional intellectual in rendering visible the deeper meanings of our lives, redefining who and what we are” (17).

6. In *Dreams of a Final Theory*, Steven Weinberg writes: “One common feature of everyone’s idea of reductionism is a sense of hierarchy, that some truths are less fundamental than others to which they may be reduced, as chemistry may be reduced to physics” (51).

7. I originally used this term in a 2007 essay entitled “Imagining Braneworlds in String Theory Technical Discourse.” Anneke Smelik also uses it in her edited collection, *The Scientific Imaginary in Visual Culture*, published in 2010. The book “explores the ways in which visual culture represents and remediates science” (9).

While Smelik contends that the term “scientific imaginary” . . . indicates that science has profound effects upon the imagination, and conversely, of the imagination in and upon science,” the emphasis is largely on the former.

8. Popularizations as a category also include semi-technical articles in magazines such as *Scientific American*, usually authored by journalists who specialize in writing about science, as well as articles by non-specialist journalists in mass media publications such as the *New York Times* or the *Guardian*. I will be focusing solely on monographs.

9. In some instances, mathematical formulae are incorporated into the text—what I call a semi-technical account; for example, Penrose’s *The Road to Reality*. Others include equations in endnotes or an appendix. But even so, by extracting these mathematical expressions from their original argumentative context, do they not lose their precise significance? Do they become what Robert Laughlin calls “baubles”? “All of us have a powerful instinct to collect things that are ‘interesting’ even when they are useless” (133, 136).

10. In the manuscript for her play *String Fever*, Jacquelyn Reingold also acknowledges Greene in particular.

11. Tensor algebra is an algebra that describes the relations between arrays of quantitative information bound to geometric spaces: in the case of general relativity, tensors of mass-energy density and space-time curvature. Riemannian geometry, unlike its predecessor, Euclidian geometry, allows for the articulation of spatial curvature. It was developed by the nineteenth-century German mathematician Bernhard Riemann.

12. In *Hyperspace*, Michio Kaku defines a *field* as “a collection of numbers defined at every point in space that completely describes a force at that point” (25).

13. In *The Fabric of the Cosmos*, Brian Greene describes space-time as a kind of “loaf” in order to illustrate how space-time may be “sliced” in different ways—an analogy that helps to clarify certain temporal paradoxes that arise with special relativity (138–39).

14. Velocity measures the motion of a body along a direction in space; or, in the internationally standard terms of measurement, meters per second. Momentum represents the product of rest mass and velocity. Acceleration measures the rate of increase in velocity with respect to time, as in, for example, a massive body falling to earth, measured as a constant acceleration of approximately 9.8 meters per second squared.

15. Quantum theory as a whole is often divided into subcategories to distinguish advances or modifications. For example: quantum mechanics, quantum electrodynamics, quantum chromodynamics, the standard model, and the various other contemporary quantum field theories, which will be described in more detail later in this chapter.

16. Particles: little “parts” of the whole. The standard model is a quantum field theory that describes three of the four fundamental forces of nature: electromagnetism, the strong nuclear force, and the weak nuclear force. It comprises a “spectrum” of fundamental particles organized into two basic categories: fermions and bosons. Simply put, fermions are particles of matter and bosons are particles of force. Developed in the early seventies, the standard model has been validated ex-

haustively by a wide range of experiments. It has thus become the canonical theory among high energy physicists.

17. Note that the terms *flavor* and *color* are figurative. A subatomic particle is not literally red.

18. “Wavefunction” is conventionally written as one word. The square of the magnitude of the wavefunction can describe, for example, the chance that a particle has of being located at a given position or, conversely, of having a certain momentum.

19. In computer programming, the term *kluge* denotes a clever, ad hoc solution to a particularly extreme aporia. Kluges often approach problems tangentially by cobbling together a hodgepodge of provisional “quick fixes” into a tenuously persisting solution. String theorist Barton Zwiebach writes: “Quantum mechanics is a framework, more than a theory” (4). To be legitimate, other physical theories (including string theory) must be “quantized” (i.e., must be made to be consistent with the constraints of the quantum theoretical framework).

20. The standard model is organized into three symmetry groups, one having to do with the strong nuclear force, one with the weak nuclear force, and one with electromagnetism. Symmetry, in this context, means that the particles of a given group conform to a specific set of rules of transformation, akin to a rotation along an axis. Generally speaking, the more axes, the more particles in the group.

21. Here is one such constant in quantum theory: “The classic example of a coupling constant is the electromagnetic fine-structure constant α [approximately $1/137$]. This dimensionless coupling constant controls the strength of the electromagnetic interactions” (Zwiebach 260).

22. Renormalization is a mathematical procedure whereby particle configurations are rescaled when momentum values get extremely large or, conversely, when distances get indefinitely small. The standard model is renormalizable, as is quantum electrodynamics. Quantum chromodynamics is also renormalizable, but that process alone is inadequate for making the model work. Most quantum field theories are not renormalizable, and thus, considered by most theorists to be ill-suited to describe physical reality. For a semi-technical explanation of renormalization, see Penrose 675–79; for a textbook exposition, see Zee 145–92.

23. The physicist Murray Gell-Mann devised the term *quark*. Reputedly, he was inspired by a phrase in James Joyce’s *Finnegans Wake*, “Three quarks for Muster Mark” (383).

24. Bosons are the group of messenger particles of force. For example, the photon for the force of electromagnetism, the gluon for the strong nuclear force, and W and Z bosons for the weak nuclear force.

25. This was not the first well-known instance of a theorist positing the existence of extra space-time dimensions. In 1919, German mathematician Theodor Kaluza, in a paper he sent to Einstein, attempted to incorporate electromagnetism into general relativity by increasing the space-time dimensions from four to five (an idea first attempted by Gunner Nordström in 1914). In 1926, this idea was modified by Swedish mathematician Oskar Klein when he proposed that the fifth spatial dimension was undetectable because it was microscopically curled-up. In general, attempts to unify fundamental forces through extra dimensions are known

as Kaluza-Klein theories. Early versions of Kaluza-Klein theory were found to contradict the, at the time, state-of-the-art experiments in quantum mechanics. It is also worth noting that physicists frequently make use of extra-dimensional mathematical models to articulate the dynamics of systems of interrelated information beyond simply the positions and momenta of particles. Hamiltonians and Riemannian geometry, for example, can readily accommodate a multitude of dimensions. (In classical and quantum mechanics, a Hamiltonian is a mathematical operator that quantifies the total energy of a given system of particles.) For a textbook proof of the need for twenty-six dimensions, see Zwiebach 206–21.

26. Bosonic string theory not only calls for the existence of the tachyon, it is the theory's "ground state," its lowest energy or vacuum state. See Zwiebach 236–42.

27. Green and Schwarz, "Superstring Field Theory"; and, as a follow-up, Green and Schwarz, "Anomaly Cancellation in Supersymmetric D=10 Gauge Theory and Superstring Theory." See Greene, *Elegant* 138.

28. Generally speaking, fermions, which include protons, neutrons, and electrons, are the grouping of quantum particles that compose matter.

29. Developed initially in 1976 by theorists Daniel Z. Freedman, Peter van Nieuwenhuizen, and Sergio Ferrara, supergravity is a field theory that integrates supersymmetry with general relativity. Like string theory, some versions posit extra dimensions. But unlike string theory, supergravity posits point-particles rather than one-dimensional extended objects.

30. One of the proposed tasks for the Large Hadron Collider at CERN is to search for sparticles.

31. These theories vary generally by: whether or not they incorporate *chirality* (an asymmetry observed in the quantum particle world); whether they incorporate open and/or closed strings—loops or strings with loose ends, so to speak; and how they organize the particle symmetry groups. All of these theories, though, do call for ten space-time dimensions and for the compactification of the six extra spatial dimensions. For a textbook exposition, see Green, Schwarz, and Witten 291–352.

32. Witten, "String Theory Dynamics in Various Dimensions."

33. Perturbation is a method for finding an approximate solution to a mathematical problem that cannot be solved exactly. See, for example, Penrose 680, 922. Witten himself is less than forthcoming on exactly what the "M" stands for, providing a diversion for theorists as they speculate on its meaning. He offers three possibilities: magic, mystery, or membrane. Others have proposed: mother (as in "mother of all theories"), monstrous, matrix, an upside-down "w" (i.e., Witten), missing, and murky. Critics would argue that, ironically, M-theory itself still suffers from an excess of degrees of freedom, just like its name. See Woit, *Not Even Wrong* 155.

34. This has to do with how the rules of commutation are formulated with respect to the extra dimensions, or in other words, how a string rotates through space-time. Simply put, commutation is an algebraic relation that is transposable (e.g., $a \times b = b \times a$).

35. For a discussion of the origins of the brane as a theoretical object, see Miller 83–84.

36. Apparently, the "F" stands for "father," as a complement to M-theory's "mother." Vafa, "Evidence for F-theory."

37. From 1995 to February 2006, arXiv.org, the preprint clearing-house for many branches of physics, published over 33,000 preprint papers in the high energy physics/theory subsection, not including cross-references. The “hep-th” subsection devotes itself to “string/conformal/field theory” preprints. Not all the papers focus on string theory, but the majority do.

38. Maldacena, “The Large N Limit of Superconformal Field Theories and Supergravity.”

39. Strominger and Vafa, “Microscopic Origin of the Bekenstein-Hawking Entropy.”

40. Polchinski, “Dirichlet-Branes and Ramond-Ramond Charges.” Instead of extending out into extra spatial dimensions, a “time-like membrane” extends into a dimension of time. Recall that, in keeping with the dictates of special relativity, within string theory, time is quantified as a space-like dimension. “D-branes” are named after the nineteenth-century German mathematician Johann Dirichlet, who pioneered work on boundary conditions for differential equations.

41. For a popular account of this “ekpyrotic” model (from the Greek, meaning “out of fire”) of the Big Bang, see Steinhardt and Turok 121–66.

42. For an exposition of some of these concepts, see Greene, *Fabric* 415–94.

43. In *The Road to Reality*, Penrose writes, “String theory operates simply with a smooth ‘classical’ background spacetime, which is not even influenced directly by the presence of a string—since the basic unexcited string itself carries no energy, and so does not directly ‘curve’ the background spacetime” (893).

44. Green writes: “Shrinking smaller than the Planck scale would be off limits not because you run into a fundamental grid, but because the concepts of space and time segue into notions for which “shrinking smaller” is as meaningless as asking whether the number nine is happy” (*Fabric* 351).

45. For a sample of this kind of research, see Banks, Seiberg, and Shenker, “Branes from Matrices.”

46. As mentioned in a previous endnote, commutation is a transposable algebraic relation: $a \times b = b \times a$. A comparable anticommutation would take the form: $a \times b = -b \times a$. In noncommutative geometry, the metrics of Euclidean and Riemannian geometry are replaced by matrices that do not commute. See Connes and Berberian 1–32.

47. Chapter 33 of Penrose’s *Road to Reality* provides a semi-technical summary of twistor theory (958–1009). In short, twistor theory maps geometric objects in Minkowski space-time onto a particular complex four-dimensional space with special features. The following is Witten’s earliest paper on the topic: “Perturbative Gauge Theory as a String Theory in Twistor Space.”

48. The Large Hadron Collider is designed to operate at approximately 14 TeV or tera electron volts. The Planck scale energy is on the order 10^{19} GeV (giga electron volts). One tera electron volt equals 1,000 giga electron volts (i.e., a trillion, as opposed to a billion).

49. See Chown 42.

50. See Vilenkin xxi–xliv; and Kibble, “Cosmic Stings Reborn?”

51. See Hoyle, et al., “Submillimeter Test of the Gravitational Inverse-Square Law: A Search for ‘Large’ Extra Dimensions.”

52. The following are some notable responses to string theory: Penrose, “Su-

persymmetry, Supra-dimensionality, and Strings” 869–933; Woit, “Is String Theory Even Wrong?” and *Not Even Wrong* 161–212; Krauss, *Hiding in the Mirror* 173–242; Smolin, *The Trouble with Physics*; interview with Sheldon Glashow in *The Elegant Universe: A Three-Hour Miniseries with Brian Greene*; Anderson, “God (or Not), Physics and, of Course, Love: Scientists Take a Leap.”

53. In its defense, physicists such as Steven Weinberg anticipate that string theory, with its radical reconceptualization of fundamental particles, as well as space-time itself, may eventually suggest new ways to formulate experiments such that current technological limitations can be overcome. See Weinberg 212–19.

54. See, for example, Susskind, *Cosmic* 343–76.

55. In *The Cosmic Landscape*, Susskind writes: “The Landscape is *not* a real place . . . It’s a mathematical construct, each of whose points represents a possible environment or, as a physicist would say, a possible *vacuum*” (90, emphasis in original).

56. For a discussion of this, see Krauss, *Hiding* 237–41.

57. Recall that perturbation is a mathematical procedure for finding an approximate solution to a problem that cannot be solved exactly. Certain problems in theoretical physics cannot be solved with a perturbative method. They require a precise solution, not an approximation.

58. Most versions of string theory assume a background space-time that must be “plugged into” the model as a starting assumption. String field theory attempts to derive space-time from calculations, obviating the need to insert space-time into the equations as an initial condition—as such, it is background-independent.

59. To reiterate: the experience of acceleration relates directly to—or, in other words, feels exactly like—the force of gravity.

60. Krauss paraphrasing Witten in *Hiding* 248.

61. See *Hiding* 191.

62. *Ibid.*, 191, 202; and Penrose 890–91, 897–902, 926–29.

63. This “I know it when I see it” argument also speaks to the notion that, echoing the radical subjectivism of Feyerabend, science is what a culture collectively marks as science.

Chapter 2

1. This argument cuts both ways, as the notorious ‘Bogdanov affair’ demonstrates. In 1999 and 2002 respectively, the Bogdanov brothers, identical twins, were awarded doctoral degrees from the University of Burgundy for theses that claimed to make original contributions to string theory cosmogony. In 2002, a controversy arose when physicists claimed that papers the Bogdanovs had published in reputable peer-reviewed journals, based on their research, were in fact illegitimate. Upon closer scrutiny, John Baez, in particular, found the papers to be “a mishmash of superficially plausible sentences containing the right buzzwords in approximately the right order. There is no logic or cohesion in what they write.” The Bogdanov affair calls attention to problems that have arisen with the hyper-specialization within theoretical physics, which makes competent peer review all the more difficult. “Ill-digested scientific jargon”—fashionable nonsense—can contaminate even the scientific disciplines themselves.